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Notes from History

# History of Thermodynamics - I: Steam Engine

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**Abstract.** Historically, the second law of thermodynamics was first to be formulated. Standard treatment of the second law of thermodynamics begins with the work of Sadi Carnot in text books or class room teaching. In this article, I will present a train of ideas related to the development of steam engine that drove the industrial revolution in Europe and culminated in laying the foundations to thermodynamics through Carnot's work.
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## 1. Introduction

Pursuit of science is to uncover what is true of the Nature based on partial and often ambiguous information obtained from our observation of it. The journey involved is fascinating in most cases, has an inspirational value and above all sharpens abilities of inquiry and reasoning for the learner.[1] The second law of thermodynamics is considered most important in the whole of Physics because of its universal applicability including the whole Universe. Standard treatment of the second law begins with the work of Sadi Carnot in text books and instruction material. In this article, I attempt to sketch a train of ideas that formed basis of and gave impetus to Carnot's work. This is the story of steam engine whose development and evolution directly aided the industrial revolution in medieval Europe.

I start with two ideas that were known since ancient times in this context. First is concerning the fact that fluids such as liquids or gases exert uniform force on objects they come in contact. Therefore if a surface is movable, then the work done by the fluid in moving the surface is equal to Pressure (Force per unit area) times the change in volume occupied by the fluid. To put things in perspective, let us consider a gas in a cylinder and arrange the movable surface to be a piston on top side. If the pressure of the gas is higher below the piston compared to atmosphere above the piston, the gas does work by spontaneously raising the piston. The second idea is with respect to using steam as the high pressure gas in the cylinder. Though there were sporadic events of demonstrations of the power of steam in doing work,[2] there had been no scientific progress in putting this idea to use. This was probably because of the availability of large number of slaves and animal force for a minority of landlords. This no longer was the case during renaissance period[3] in Europe and the stage was set for machines to replace slaves. But to unleash the power of steam, one had to wait for a clear understanding of atmosphere and its absence.

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## 2. Atmosphere

It was observed that fluids have a tendency to fill the space where there is a lack of it. In 1641, Italian engineers of Cosmo II dé Medici constructed a suction pump.[4] This flushes out the air in a pipe and creates vacuum. One end of the pipe is placed in water in a well so that water can be drawn up from the well. To their surprise, they observed that whatever they did, the water did not raise beyond a height of 32 feet ($\approx$ 975 cm).

They approached Galileo for an explanation. One of Galileo's pupil Evangeliste Toricelli understood that the atmosphere has a weight. It is the weight of the atmosphere that pushes the water up the pipe into the vacuum and hence the observed limit. Toricelli showed that if mercury is used instead of water, since its density is high, it will raise to a height of 28 inches ($\approx$ 71 cm). He invented barometer to measure the atmospheric pressure. He concluded that we live in the bottom of a sea of air. Blaise Pascal in 1647, argued that if we live under a sea of air, then the atmospheric pressure must decrease if we move to higher elevations, similar to what happens under water. In 1648, Florin Périer climbed the 4800 foot Puy de Dóme (France) with a mercury barometer and found that the mercury column fell by 3.5 inches ($\approx$ 9 cm).

Though Toricelli understood the atmospheric pressure, its power was dramatically demonstrated by Otto van Guericke in Germany during 1657, where he joined two hemispheres to create a full sphere and each hemisphere is hooked to a team of eight horses. He used a suction pump to create vacuum in the sphere. The two teams of horses failed to pull the two hemispheres apart. This turned out to be a spectacular demonstration of the power of atmospheric pressure against vacuum to even common public. It was becoming clear that if vacuum can be created, work can be extracted from atmospheric pressure. But how to create vacuum efficiently was a major concern. The power required to operate suction pump is not economical to produce vacuum in large scale structures.

## 3. Steam Engine

Huygens in 1673 designed a piston-in-cylinder engine using explosion of gunpowder.[5] Explosion of gun powder at the bottom of the cylinder expels the air from the cylinder and balances the piston against the atmopsheric pressure. As the combustion products are cooled, pressure beneath the piston is reduced and piston is forced down by the atmospheric pressure raising the weight attached to the piston through a wire passed over a pully arrangment.

During this period, Gottfried Leibniz from Germany thought the Universe is a big living machine. He defined soemthing called a *living force* which existed with every object and is exchanged when objects collide. He further proposed that the amount of living force is conserved in the Universe. He observed that in gunpowder, steam and fire this living force is released and wondered if such a released living force can be captured and put to use. He discussed with Denis Papin, then an assistant to Huygens, on these ideas.

Denis Papin worked to improve Huygen's engine. In 1690, Denis Papin made a significant improvement over Huygen's engine. He first got rid of the gunpowder. He observed that a small quantity of water when turned into vapour by heat, it has elastic force like air (the living force of Leibniz). Upon cooling, the vapour becomes water with no trace of the said elastic force. Papin's engine is similar to that of Huygens piston-in-cylinder engine. A small amount of water was placed in a cylinder and the bottom of the cylinder was heated using fire. The evaporated water raises the piston which is then locked. The fire is removed. The vapour condensed to water creating a vacuum and then the lock is released so that the piston is pushed down by atmospheric pressure raising the weights attached to it through a pulley arrangment.

By the end of 17th century, most forests near the population centers are used up in England. To meet the energy needs of the population, the coal was resorted to and coal mining had become important. One of the difficulty faced by mining industry was that water present in mines and it was necessary to remove this water for further mining activity. It was done using horses, but it was very expensive. In 1698, Thomas Savery patented his engine which he named as *The Miner's Friend*. An important step in Savery's engine is that the boiler in which steam is generated is separated from the cylinder in which condensation takes place. A metal vessel is connected from the top to a boiler and from the bottom to a stagnated water body also through a pipe. Valves are fixed on both the ends. First the steam generated in boiler is allowed to enter the vessel by opening the top valve and then closed. Water is sprayed outside the vessel to cool and condense the steam and there by create vacuum. Bottom valve is opened so that the water is sucked into the vessel from the depths of mines. The bottom valve is closed and high pressure steam is allowed from by opening the top valve to flush the water collected out of the vessel. This simple design however works within the Toricelli's limit of 32 feet. When the depth of the mining site is more than 32 feet, the engine needs to be placed below the ground making the operation difficult. Also boilers needed to generate high pressure steam had the risk of blowing off.

In 1712, Thomas Newcomen combined the ideas of previous century and built a successful engine that became very popular and useful to mine workers. He based his design along the lines of Huygens and Papin, the piston-in-cylinder type, but also adopted the idea of separating the boiler from the cylinder from Savery's engine. Since this is the first commercial steam engine that served England for next fifty years, let us pay attention to changes Newcomen incarporated over previous designs.[6]

- The boiler and piston-in-cylinder are kept separate (similar to Savery's engine)
- The piston is connected to a beam at one end and the other end is connected to a pump that is lowered into the mining site with center of the beam is clamped to a fixed support (This arrangement allowed one to draw water beyond Toricelli's limit of 32 feet).
- The steam in the cylinder is condensed by injecting a jet of water into the cylinder (an improvement over natural cooling by Papin and spray of water outside the cylinder by Savery).[7]

The working of Newcomen steam engine is as follows[8]: Steam enters the cylinder from a boiler and balances the piston against the atmospheric pressure. A water jet from a water tank is injected in to the cylinder. This results in condensation of the steam and vacuum is produced. The atmospheric pressure pushes the piston down resulting in a power stroke. The piston is connected to one end of a beam whose other end is connected to a pump lowered to a mining site. With every power stroke the mining end of the pump draws water out of the mining site. The codensed water is pumped out by a pipe. The weight of the pump and injected steam restores the piston to the top of the cylinder. The engine was known to perform about ten power strokes per minute and lead to releasing of horses for the task. The efficiency of steam engine was low (thermal efficiency is 0.5) and efforts over next half a century doubled the efficiancy notably due to efforts of John Smeaton.

## 4. Enter James Watt

In 1763, James Watt was given the task to repair a small model Newcomen steam engine that belongs to the University of Glasgow. After making it work, he observed that the boiler could not supply steam to the cylinder for more than a few power strokes. He undertook a truly scientific study of the working of Newcomen atmospheric steam engine by analizing every part of the engine. His studies not only improved the design of steam engine and provided much needed power to carry industrial revolution on its shoulders, but also laid the foundation to the whole of thermodynamics. Let me list some of his studies and corresponding improvement for the engine here.[9]

- The cylinder in Newcomen engine was made of brass, which conducted heat away from the steam. He observed that the cylinder was so heated when steam was admitted that it could not be touched by hand, all that heat is a loss as far as performance of the engine is concerned. By means of a systematic investigation, he noticed that in every stroke there is a loss of heat when cylinder is cooled upon injection of water jet to condense steam and create vacuum. Through careful experiments, he deduced that the weight of steam at atmospheric pressure is one eighteen hundredth part of the weight of equal volume of cold water. Then he observed based on the water that is used up in boiler to fill the cylinder with steam is four times the water required to generate the steam needed to fill the cylinder.[10] He then concluded that three fourths of the steam is wasted. Watt's attempt to improve the engine was to use a wooden cylinder soaked in linseed oil and baked to dryness. He found advantage in the economy of the steam.
- In the next stage, Watt determined on the qantity of cold water required to produce condensation of a given weight of steam. He found that one pound ($\approx$ 0.45 kg) of stean contained enough heat to raise about six pounds of cold water used for condensation from temperature of 52$^o$ F ($\approx$ 11$^o$ C) to the boiling point. On discussion with his friend Joseph Black, a chemist at University of Glasgow, Watt learnt the concept of latent heat, the heat concealed in steam.[11] He realised that the concealed heat in the steam is what provides the elastic force for the steam. Watt, having known all the facts related to steam, its temperature, elasticity, weight and concealed heat, he was able to reason correctly on all the cirumstances effeccting the performance of an engine. It was clear that a great quantity of heat is contained in a certain quantity of steam and the economical use of the steam was of more importance to the improvement of engine, than the construction of the boiler and furnace, which had been the main object of former efforts to improve the engine. This is a conceptual shift which influened Sadi Carnot 60 years later to his much celebrated abstraction of the working of a heat engine.
- Watt's Eureka moment occurred when he was walking through a Glasgow Green

park on a Sunday in May 1765. In Watt's own words, "The whole thing suddenly became arranged in my mind". This is the revolutionary idea of a separate condenser, which eventually set the industrial revolution in motion. In Papin's engine, boiling water to steam and condesation of steam to water occurred in the same cylinder. Savery and Newcomen separted the boiler and the produced steam was injected in to the cylinder, where condensation of steam takes place in the cylinder (by injection of a jet of cold water in Newcomen engine). Watt designed a separate vessel called condenser maintained at lower temperature where steam from the cylinder reaches through a pipe, gets condensed and creates vacuum, there by maintaining the cylinder always hot. This minimised the loss of heat resulted in re-heating the cylinder in every stroke.[12]

- Watt further observed that the piston used in the cylinder was pushed down by the atmospheric pressure and this contact with atmopshere cooles the piston and walls of the cylinder during the discent of the piston. He decided to minimize this loss, by enclosing the cylinder in a case filled with steam from the boiler so that the piston is pushed by the steam against the vacuum created. Here the temperature of the cylinder and its enviroment are same, namely the boiling temperatue of the water.[13]

Watt's atmospheric steam engine was used in mines, textile and other industries. Steam engines were made mobile and they were put to use for military purposes. England gained its economic and military supremacy over other countries based on the technology of steam power. Humiliated by the defeat France suffered in war with England, Said Carnot set himself the task of theoretical analysis of the efficiency of steam engine and his sole book titled *Reflection on the motive power of fire* published in 1824 at the age of 28 turned out to be a creative leap of a genius[14] and provided the basis for the formulation of much celebrated second law of thermodynamics in the middle of 19th century.[15]

## Notes and References

[1] The presentation here is however subject to my limitted appreciation of a small but representative pieces of work sampled from a large body of literature

[2] Two thousand years ago, Hero of Alexandria demonstrated the power of steam by running it into a metal sphere from which protruded two pipes $180^o$ apart, each taking a $90^o$ turn at the end such that they pointed in opposite directions. As the steam rushed out of these pipes, the resulting thrust from eah spun the sphere on a rod.

[3] Renaissance is a French word meaning "rebirth". The renaissance period was roughly around A.D 1400 to A.D. 1600 which marked rebirth of humanism and lead to new discoveries in science, arts and philosophy

[4] Robert T. Hanlon (2020). Block by Block: The historical and theoretical foundations of thermodynamics (1st ed.). Oxford University Press.

[5] Henry Winram Dickinson (1939). A short history of the steam engine. Cambridge University Press.

[6] Malcolm S. Longair (2020). Theoretical concepts in Physics: An alternative view of theoretical reasoning in Physics (3rd ed.). Cambridge University Press.

[7] Newcomen initially cooled his cylinder by spraying water outside the cylinder as in the case of Savery's engine. When there was an accidental leak of water into the cylinder, the condensation occured so fast and hence this improvement was serendipitously incarporated in the design.

[8] See for a nice animation Wikipedia.org - Newcomen atmospheric engine

[9] Farey John (1827). A treatise on the steam engine : historical, practical, and descriptive. London : Printed for Longman, Rees, Orme, Brown and Green.

[10] Robert Henry Thurston, (1877). The growth of the steam engine. Popular Science Monthly, **12**, 1–41.

[11] Donald Fleming, (1952). Latent Heat and the Invention of the Watt Engine.Isis, **43** (1) 3.

[12] More importantly it highlighted the possibility of a later abstraction that the work done is caused by the flow of heat from high temperature to low temperature by Sadi Carnot.

[13] This improvement was abstracted by Carnot as isothermal expansion as a first step in his famous Carnot cycle to maximize the efficiency.

[14] Wayne M. Saslow, (2020). A History of Thermodynamics: The Missing Manual. entropy, **22** 77.

[15] I plan to write on the way the second law was formulated in the next article.